Jupiter's Nitrogen Isotopic Ratio from Cassini Observations: Some Astrophysical Implications

Mian Abbas
NASA – Marshall Space Flight Center

And

Andre LeClair
University of Alabama at Huntsville

Co-Investigators and Collaborators

- **UAH:** A. LeClair, S.T Wu
- **NASA/GSFC:** B. J. Conrath, F. M. Flasar, V. G. Kunde, C. A Nixon, R. K. Achterberg, G. Bjoraker, D. J. Jennings
- **Univ. of Hawaii:** Tobias Owen
- **JPL:** Glenn Orton

(This presentation is based on a paper in press for publication in the Astrophysical Journal, Feb. 2004.)

The Cassini-Huygens Mission

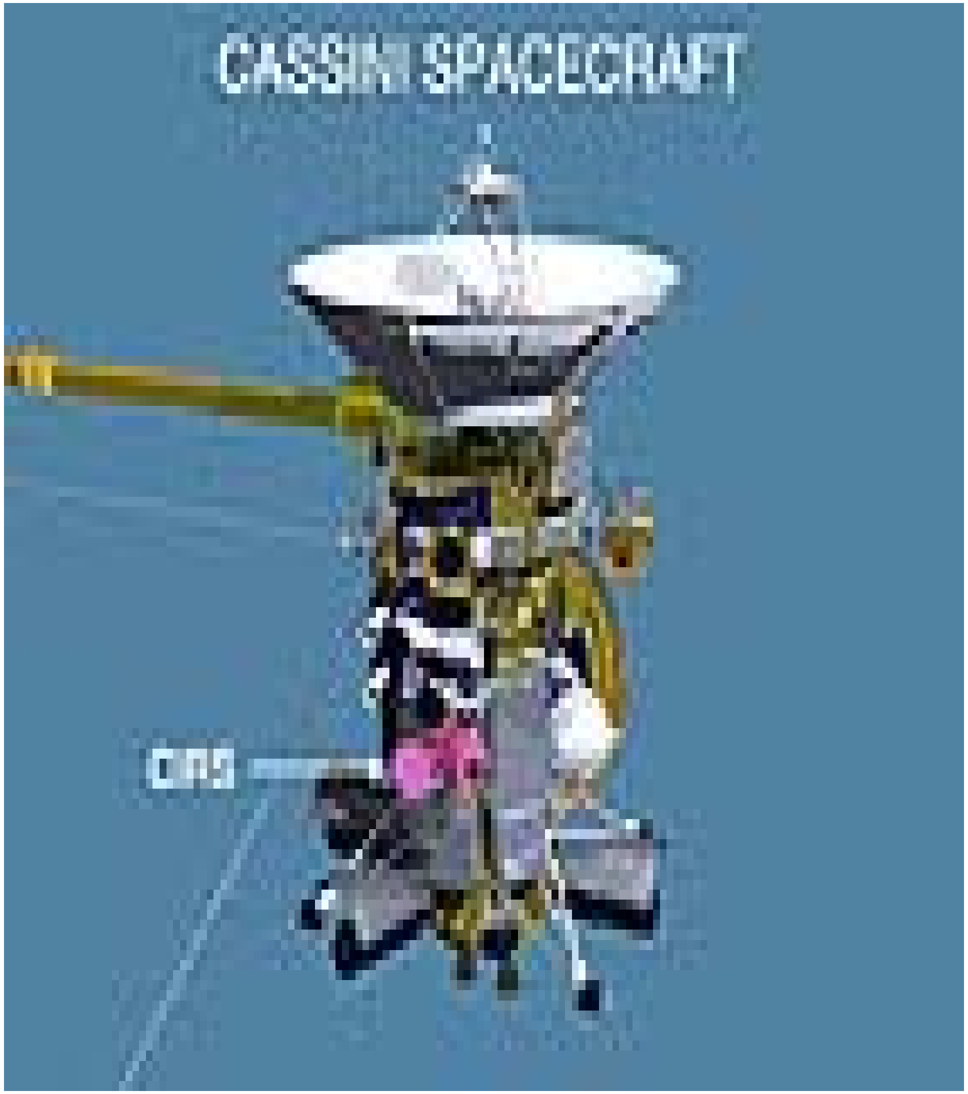
- The mission is a joint NASA-ESA mission. The spacecraft launched in October 1997 for exploration of Saturn, its rings and satellites, in particular its largest moon Titan.
- The French Huygens-Probe with a number of instruments is programmed for a balloon-landing on Titan.
- Arrival for Saturn orbit insertion on July 1, 2004, for a four year tour.

Cassini Launch and Spacecraft

The Cassini spacecraft was launched on October 17, 1997, with 12 instruments for a four year orbital tour of Saturn and its satellites, and with Huygens Probe for landing on Titan.

The Cassini Spacecraft

- **The Cassini Spacecraft** carries 12 instruments with a wide range of objectives covering particles and field, neutral particles, dust, atmospheres, surface chemistry, planetary interior etc. Covers various regions of the electromagnetic spectrum, involving visible, radio, infrared, and UV instruments.
- **Objective**: Exploration of the Saturnian system for investigations of the origin and evolution of the solar system.



Composite Infrared Spectrometer (CIRS)

- A pair of far- and mid-infrared thermal emission spectrometers sharing a 50-cm beryllium Cassegrain telescopes, for nadir and limb viewing
- Spectral range: 10-1400 cm^{-1} (1 mm – 7 μm)
- Spectral resolution: Variable from 0.5 to 20 cm^{-1}

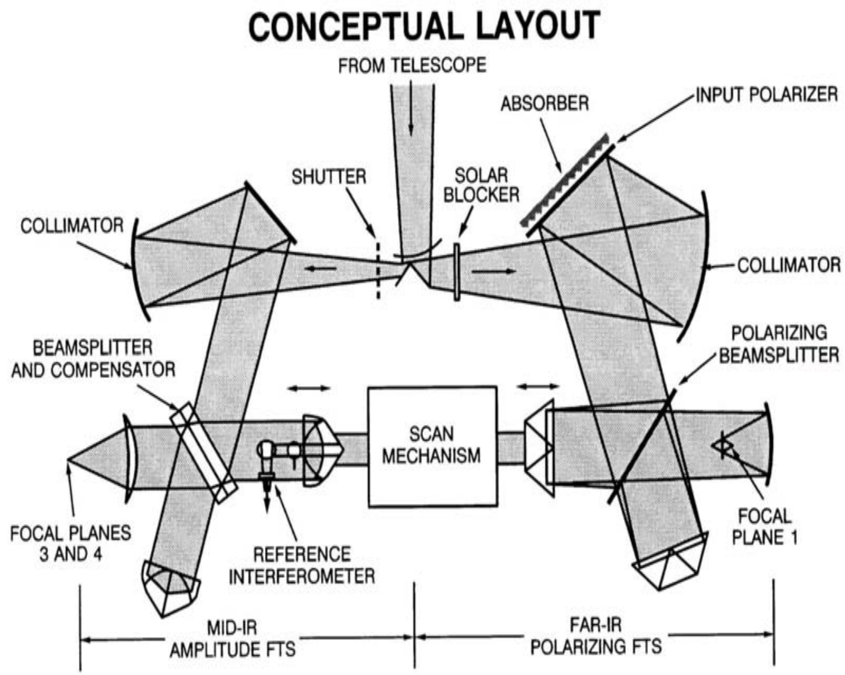
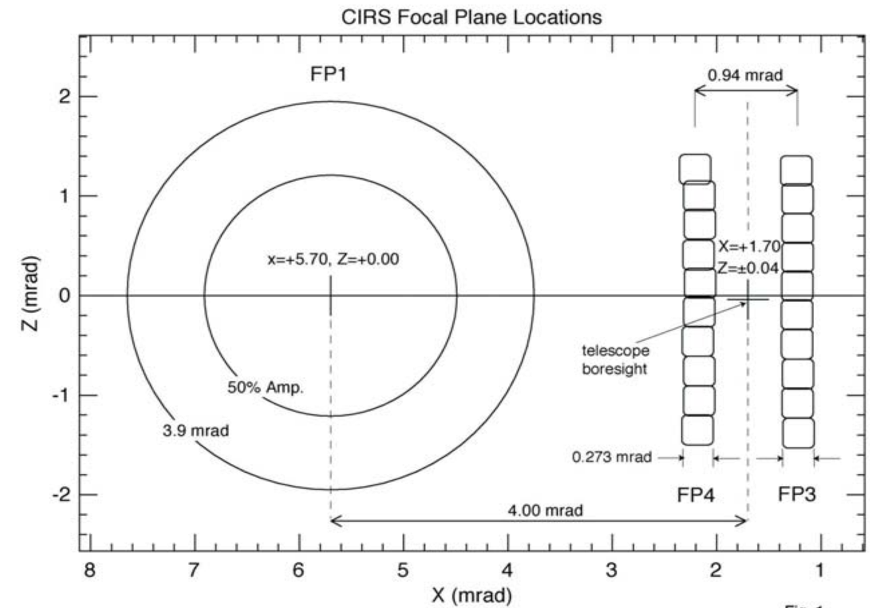


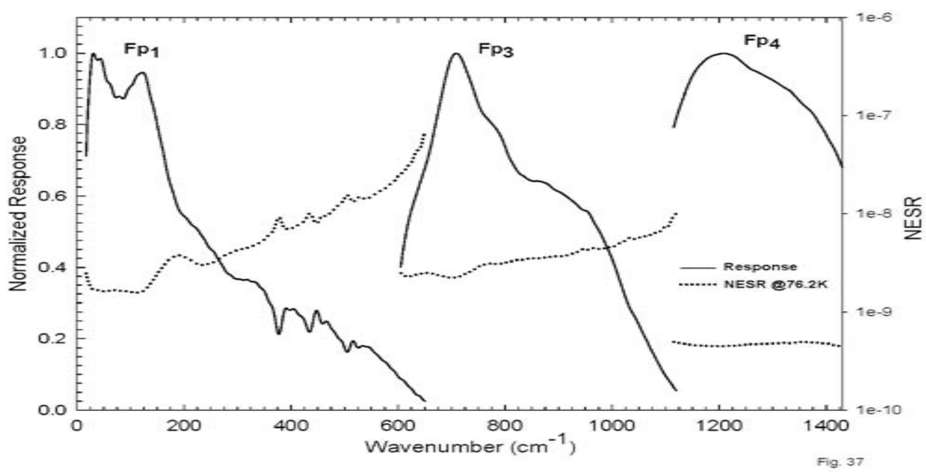
Fig. 35

- Far-Infrared spectrometer is a Martin-Puplett type interferometer covering the 10-600 cm^{-1} region.
- The mid-IR interferometer is a conventional design covering 600-1400 cm^{-1}.

Composite Infrared Spectrometer (CIRS)

- Far-Infrared spectrometer consists of a focal plane (FP1) with two thermopile detectors with a 3.9 mrad FOV covering the 10-600 cm^{-1} region.
- The Mid-IR interferometer has two focal planes (FP3, FP4), in two band passes.
- FP3 is with a 1x10 photoconductive HgCdTe detector arrays covering 600-1100 cm^{-1}.
- FP4 is with a 1x10 HgCdTe photovoltaic detector covering 1100-1400 cm^{-1} . Each detector pixel has a FOV of 0.276 mrad.





CIRS Observational Modes

- Observations may be made in limb or nadir viewing modes for global mapping.

- Limb observations provide a wider observable pressure range with much higher spatial resolutions. Data analysis, however, requires retrieval of the viewing angles from the observed spectra.

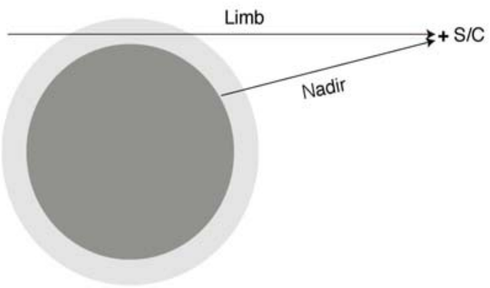


Fig. 2

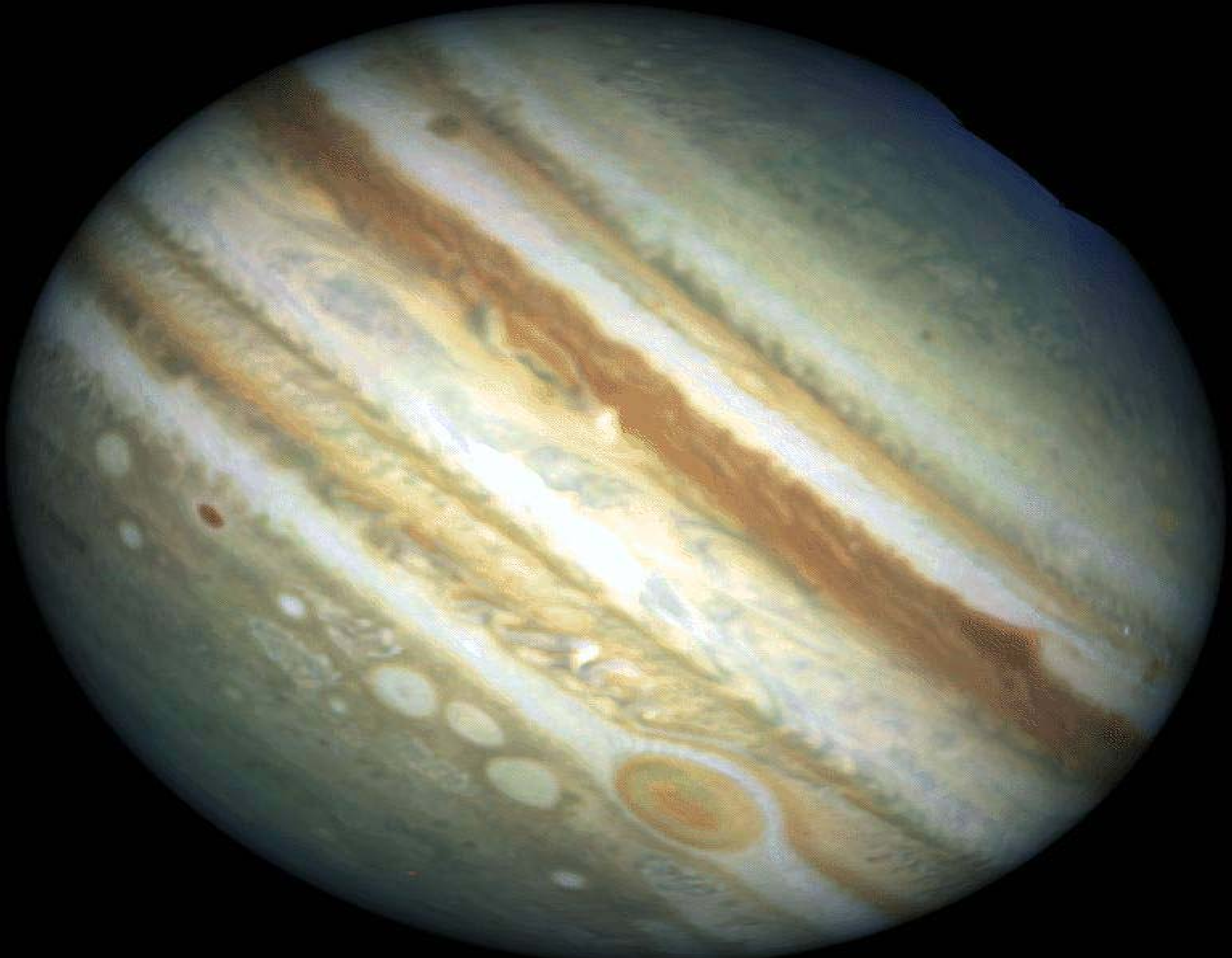
- Spectral Regions and Resolutions:

  Far-infrared: 10-600 cm^{-1}, or 1mm to 16 μm.
  with 0.5 cm^{-1} to 20 cm^{-1} spectral resolution.

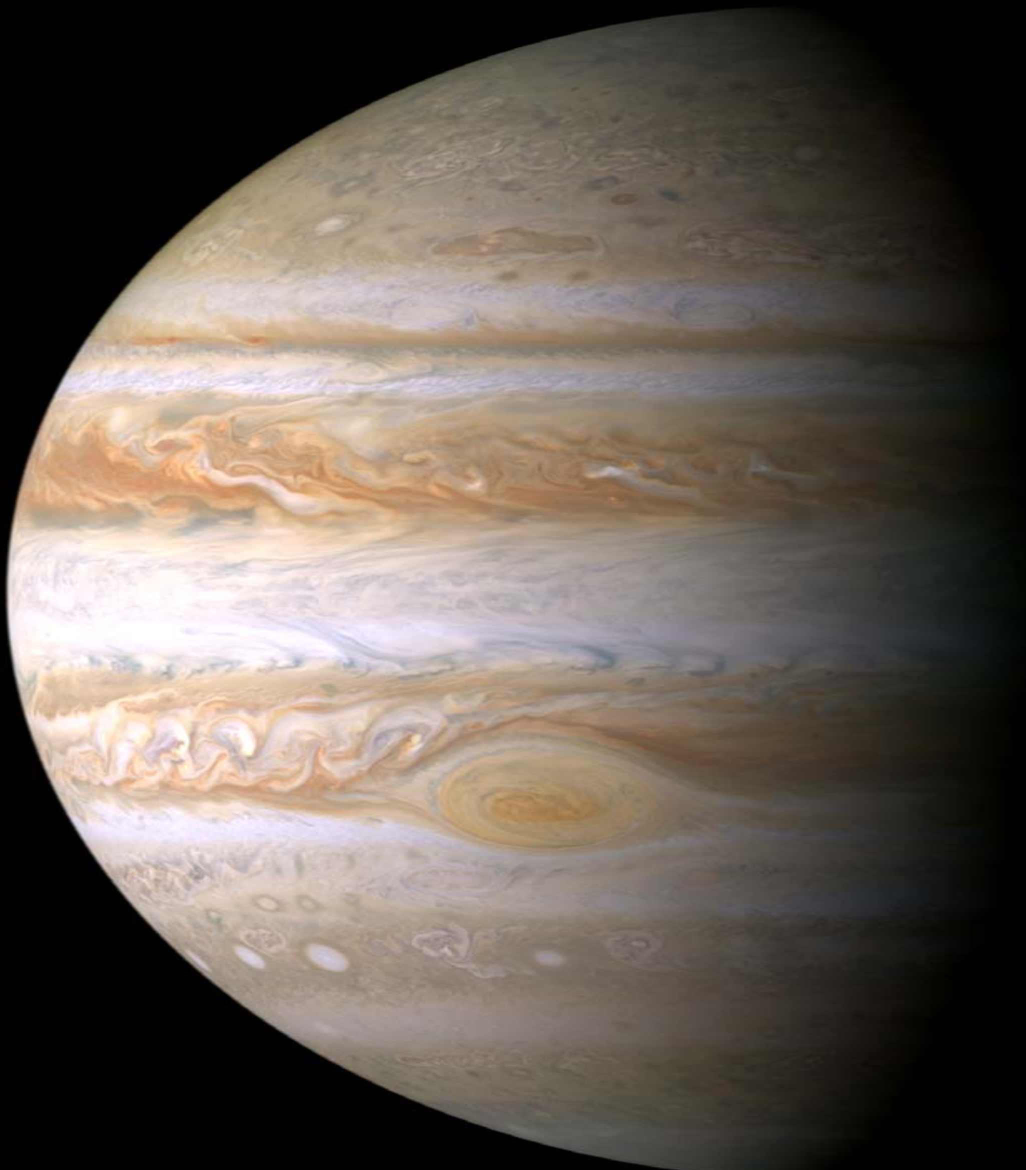
  Mid-infrared: 600-1400 cm^{-1}, or 17 μm to 50 μm.
  with 0.5 cm^{-1} to 20 cm^{-1} spectral resolution.

- Information obtained from various spectral regions in limb and nadir viewing modes may be combined for retrieval calculations of the atmospheric parameters.

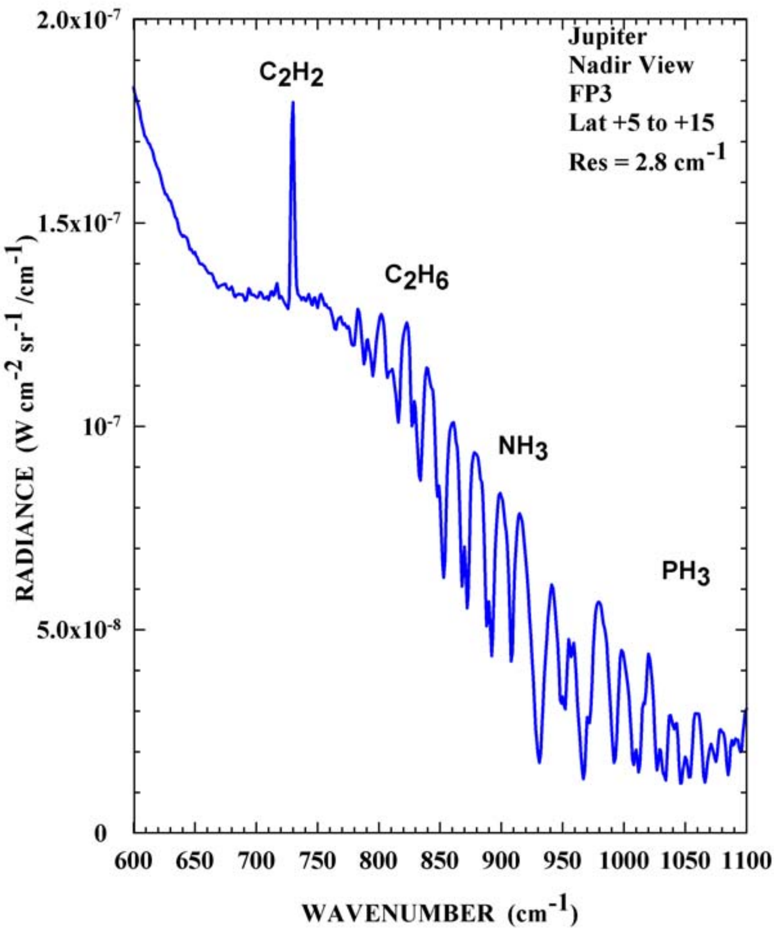
Spacecraft flew by Jupiter in Dec. 2000-Jan. 2001: Unique Global Infrared Spectral Maps of Jupiter Obtained.

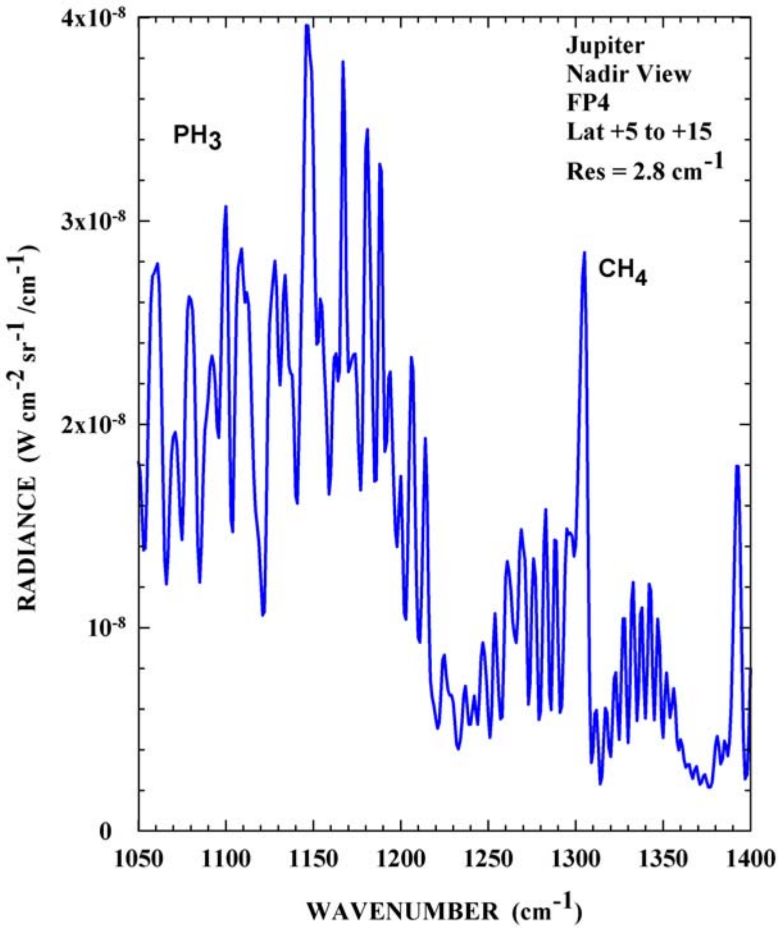


Spacecraft flew by Jupiter in Dec. 2000-Jan. 2001: Unique Global Infrared Spectral Maps of Jupiter Obtained.



Observed Infrared Spectra of Jupiter





Production of Nitrogen in the Galaxy: The CNO cycles

- Measurement of nitrogen isotopic ratio $^{14}N/^{15}N$ is of great scientific interest because of its relevance to formation of nitrogen isotopes by nucleosynthesis in the CNO cycles, their evolution in the galaxy, as manifested in the local ISM, the solar system and the planets.

- Nitrogen is believed to be formed by nucleosynthesis in the interior of stars in the CNO cycles by the p and α capture reactions.

- Production of ^{14}N in long lived, intermediate and low metallicity stars.

- ^{15}N is believed to be synthesized in massive stars with short life times that become type II supernovae.

- Current models do not produce sufficient amounts of ^{15}N, and measurements indicate conflicting results, referred to as the "nitrogen puzzle"

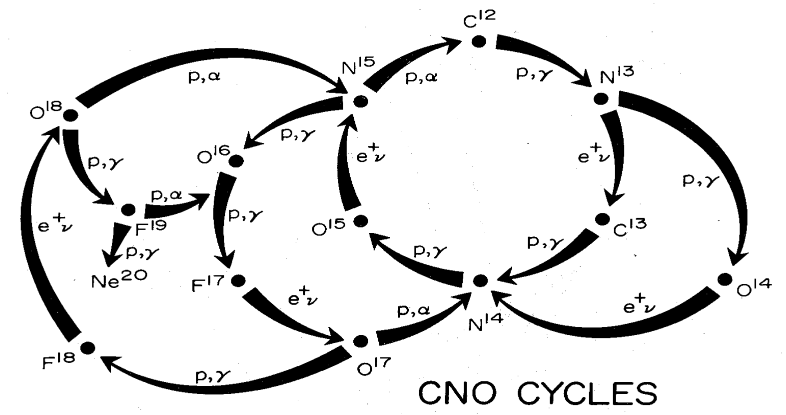
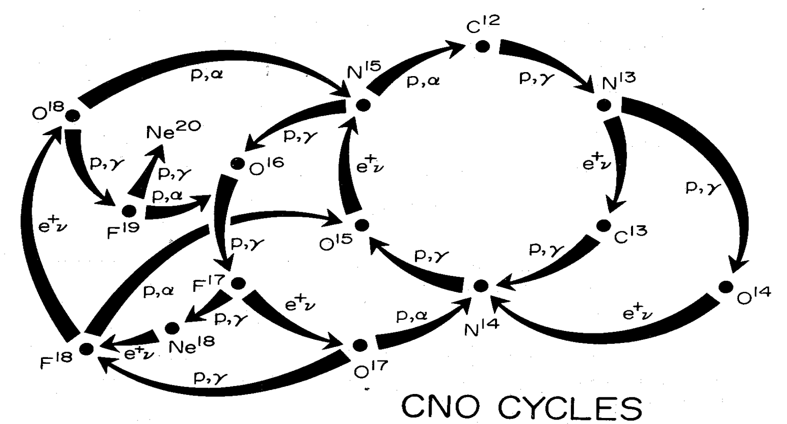
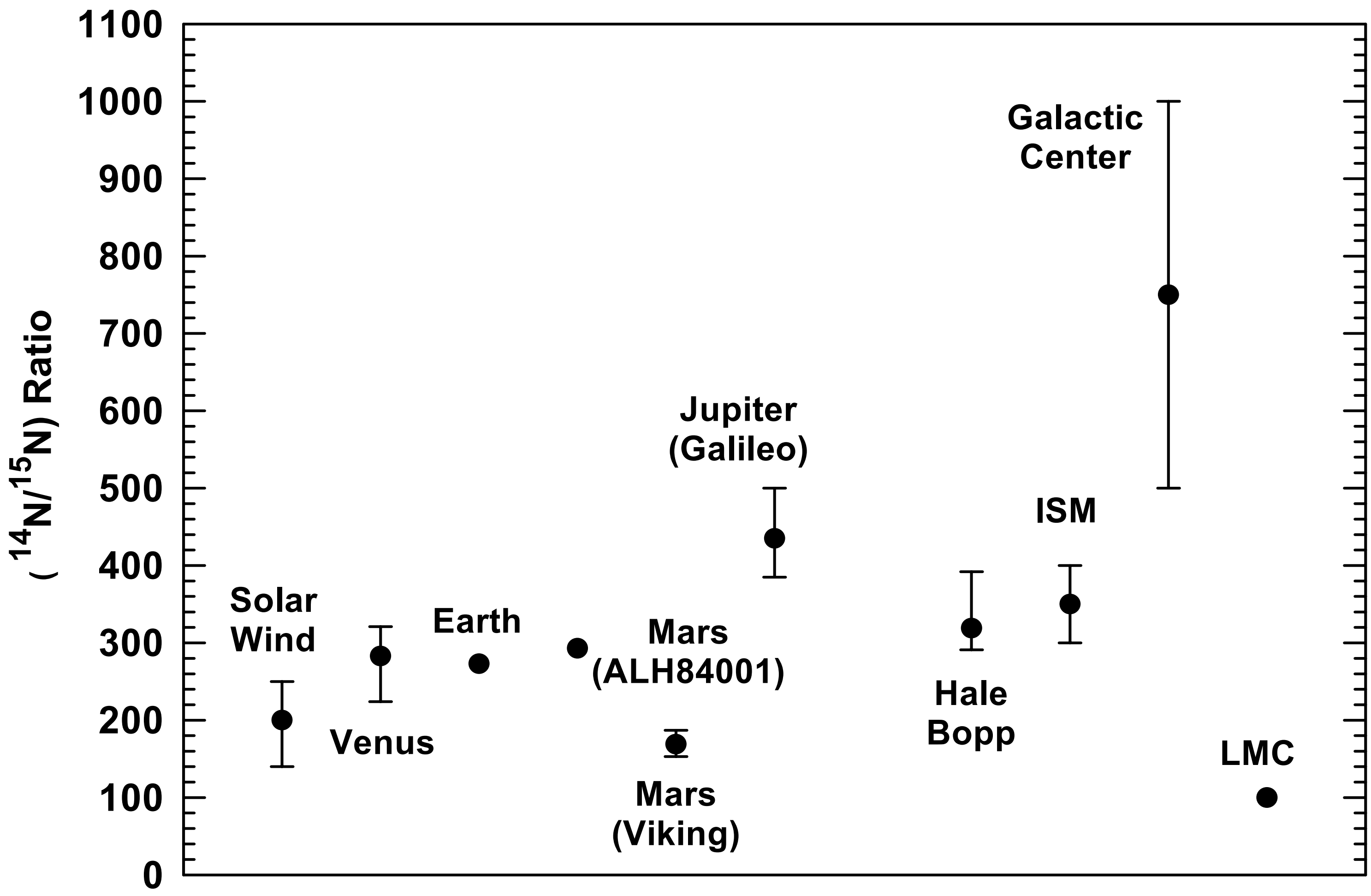


Fig. 1. CNO Cycles



(From: G. R. Caughlan, The CNO Cycles, in, J. Audouze (Ed.) CNO Isotope in Astrophysics, 1977)

Variation of Nitrogen Isotopes in the Galaxy



Jupiter's Atmospheric Thermal Structure and Composition

- **Thermal Structure**

  Temperature at 1 bar: ~170 K

  Tropopause temperature ~ 110 K

- **Composition:**

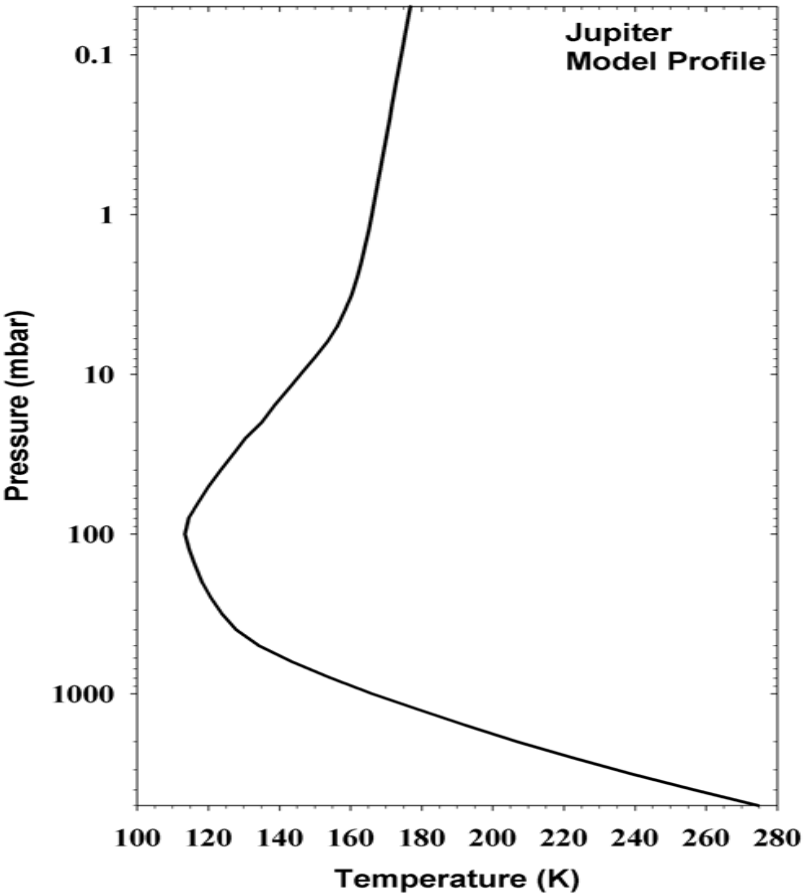
  Major Constituents: H_2 ~ 86.3%, He ~ 13.4%

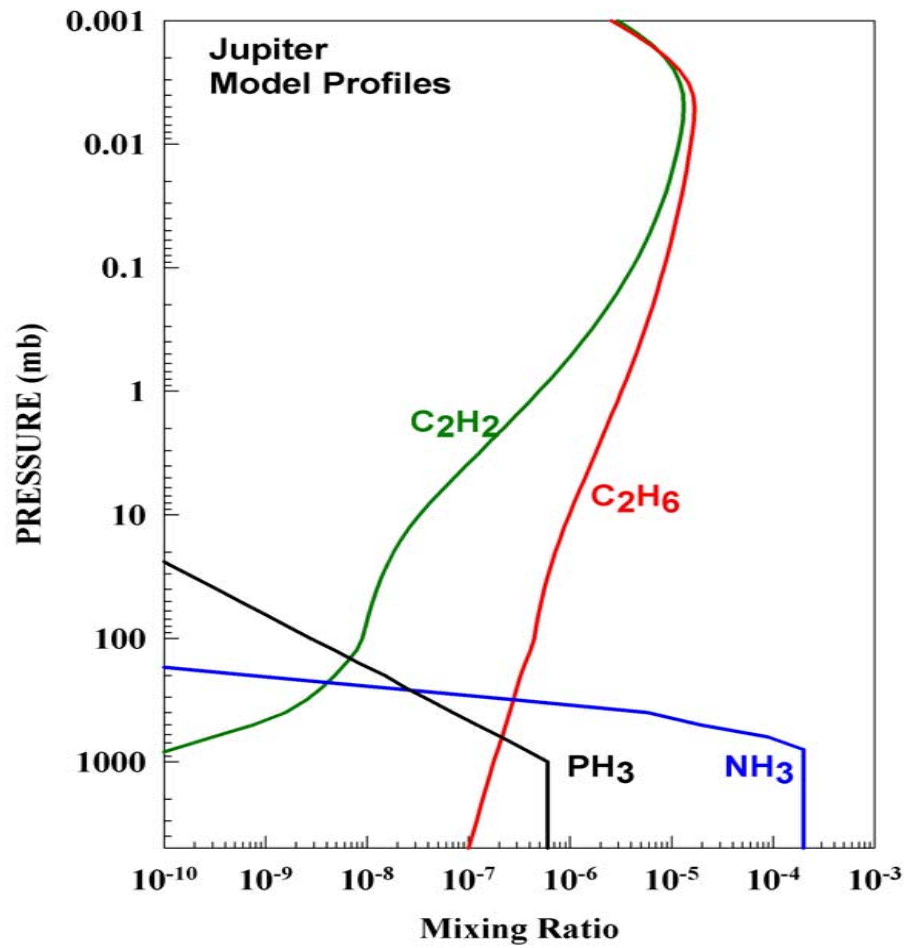
  Minor Constituents: CH_4, $^{14}NH_3$, $^{15}NH_3$, PH_3, C_2H_2, C_2H_6, C_4H_2, C_2H_4

- **Complex hydrocarbons and nitriles** formed through photochemical/electron collision reactions.

- **Clouds: NH_3-ice, NH_4SH, and $(NH_4)_2S$** at ~700 mb and at lower levels.

Jupiter's Model Atmospheric Thermal Structure and Composition





Radiative Transfer Model

Observed radiance:

$$I_\nu(\theta) = \varepsilon_{\nu s}\tau_{\nu s}B_\nu(T_s) - \int_{ps}^{pt} B_\nu(T)\; C_\nu(\theta, p, T, n_i)\, d\ln p$$

Transmittance:

$$\tau_\nu = \exp\left[\int \sum_i k_\nu^i(p,T)\; du_i \right]$$

Gas column density:

$$du_i = n_i m_i ds$$

Contribution Functions:

$$C_\nu = B_\nu(T)\frac{\partial \tau_\nu}{\partial \ln p}$$

$$C_\nu = \frac{\partial B_\nu}{\partial T} \cdot \frac{\partial \tau_\nu}{\partial \ln p}$$

$$C_\nu = \frac{\partial \tau_\nu}{\partial \ln u_i} \cdot \frac{\partial B_\nu}{\partial \ln p}$$

Spectral Inversion Technique

- Non-linear least squares inversion technique
- A set of frequencies ν_i with radiances I_ν is selected with contribution functions sharply peaked over a range of pressure levels in the atmosphere.
- Assume the radiance I_ν is a function of a set of parameters $q(q_1, q_2, ... q_L)$

  for $L \geq 1$, and frequencies ν_i for $i = 1, 2, \ldots, m$.

- For the inverse problem, $I^o = I(q;\nu_i)$ is known for given ν_i and solutions q_j, for $j = 1, 2, \ldots, L$, are to be determined.

- For $m > 1$ and $L = 1$, the problem is over determined and an iterative solution $q = q^o$ is uniquely determined in the least-mean-square sense, starting with an initial guess value of $q = q^1$, until the difference between the observed and the calculated value of I_ν is less than the noise level.

Spectral Inversion Technique (contd.)

Relaxation Equations:

$$I_i^n = I(q^n) \qquad r_i^n = I_i^o - I_i^n$$

- Assuming an initial guess model atmosphere, radiances are calculated for the selected frequencies and compared with the observed values.

$$\sigma^n = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(r_i^n)^2}$$

- The atmospheric parameters (T, gas mixing ratios) are corrected at the peaks of the contributions functions (CFs) till the rms differences approach the noise level.

$$q^n = q^{n-1} + \frac{\sum_{i=1}^{m}\left(r_i^{n-1} a_i^{n-1}\right)}{\sum_{i=1}^{m}\left(a_i^{n-1}\right)^2}$$

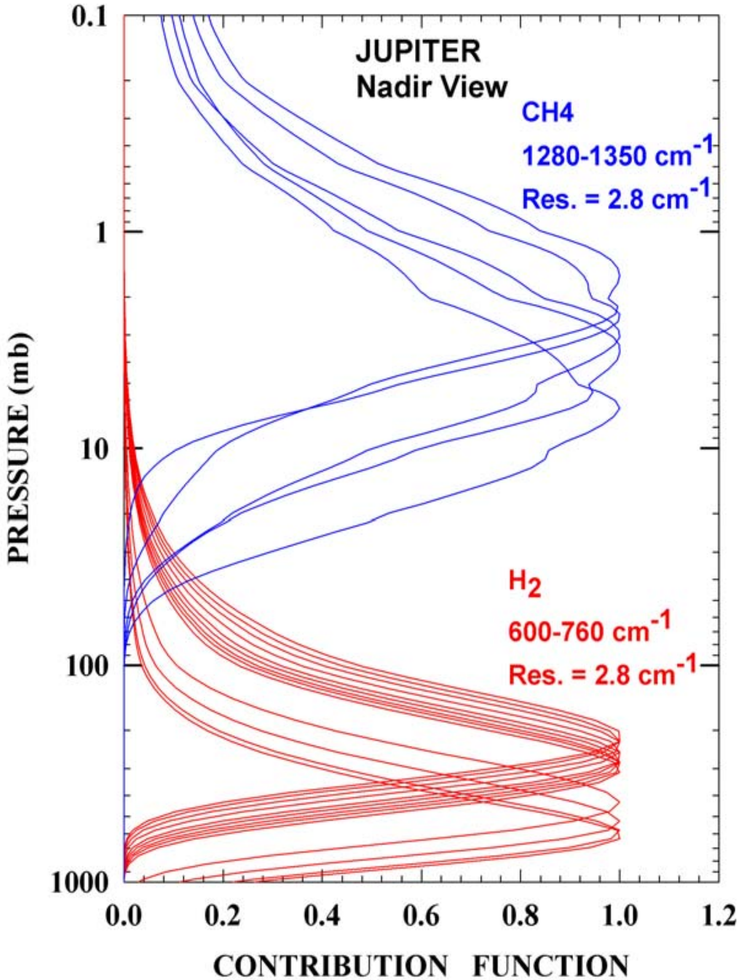
- The regions above and below the CFs are scaled appropriately

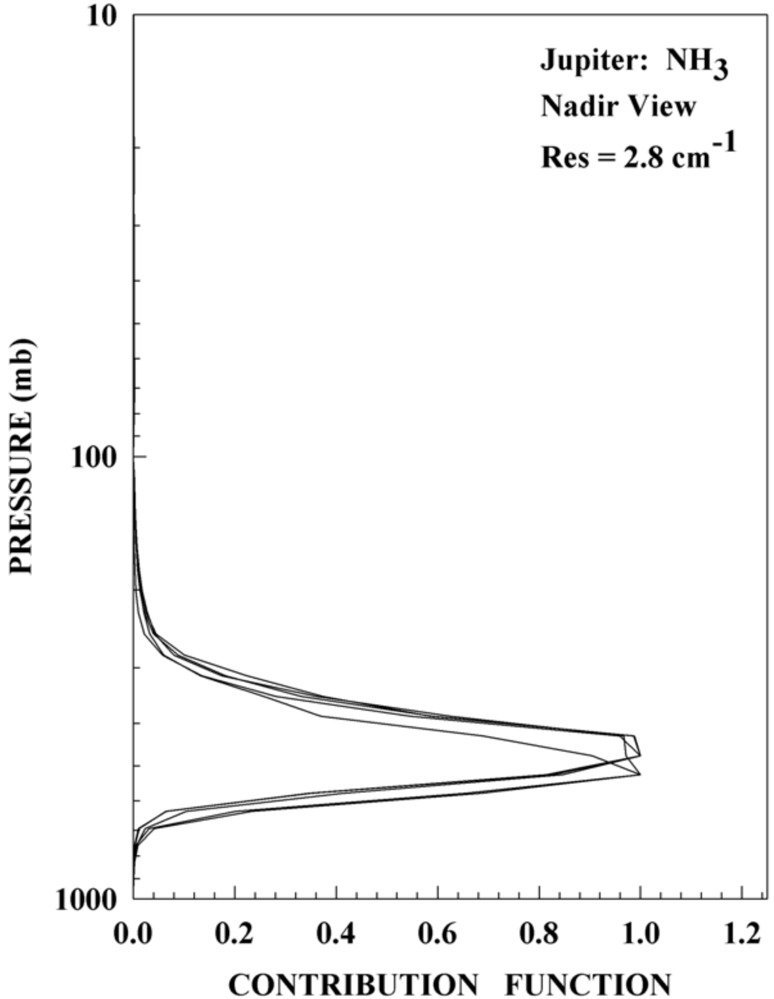
$$a_i^n = \left(\frac{\partial I\left(q;\nu_i\right)}{\partial q}\right)_{q=q^n}$$

Analytical Procedure for Retrieval of Nitrogen Isotopic Ratio

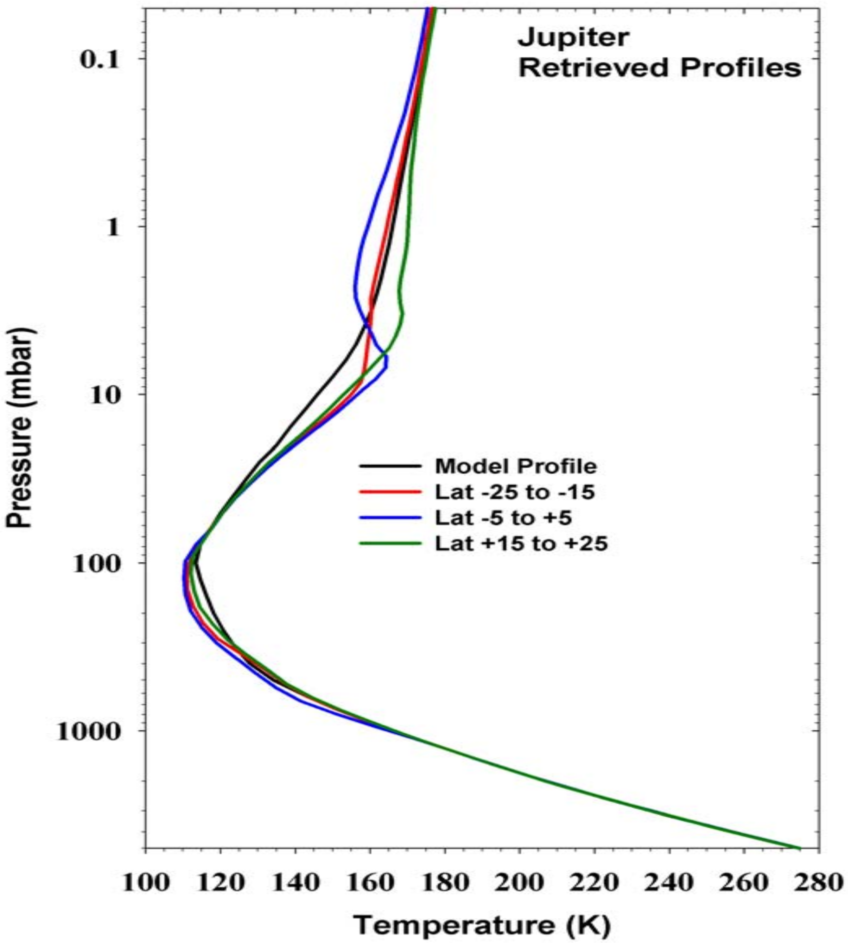
- **Observation Modes:** Only nadir viewing, at R_J ~137-250
- **Data utilized:** Low Res. spectra (~ 20,000 @ 2.8 cm^{-1}), Dec. 30-Jan. 15, 2001; High Res. spectra (~11000, @ 0.53 cm^{-1}), Nov. 30- Dec. 13, 2000; Latitudes: 75°N to 75°S; Longitudes: wide range.
- **Averaging:** Data averaged over 10° latitude-bins.
- **P/T global profiles:** retrieved over a 10° latitude grid using 2.8 cm^{-1} spectra.
- **$^{14}NH_3$** profiles retrieved from both 0.53 cm^{-1} and 2.8 cm^{-1} spectra using about 38 selected frequencies in the 860-960 cm^{-1} region.
- **$^{15}NH_3$** retrieved from 3-isolated spectral features at 863, 883, and 903 cm^{-1} in the high resolution 0.53 cm^{-1} spectra.
- **PH_3** profiles retrieved from the 2.8 cm^{-1} data.
- **C_2H_6** retrieved from the 0.53 cm^{-1} data.
- **Other minor constituents**: model profiles.

Contribution Functions for Temperature and NH_3 Retrievals

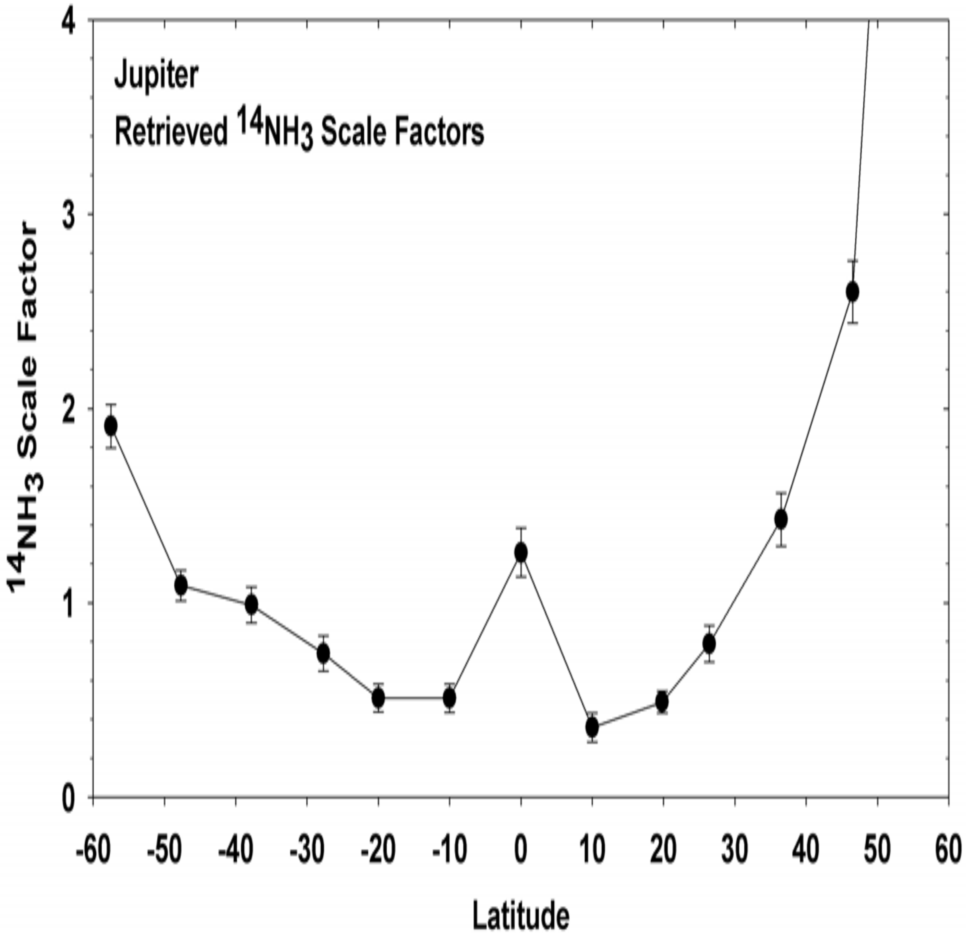




Infrared Spectra of Jupiter

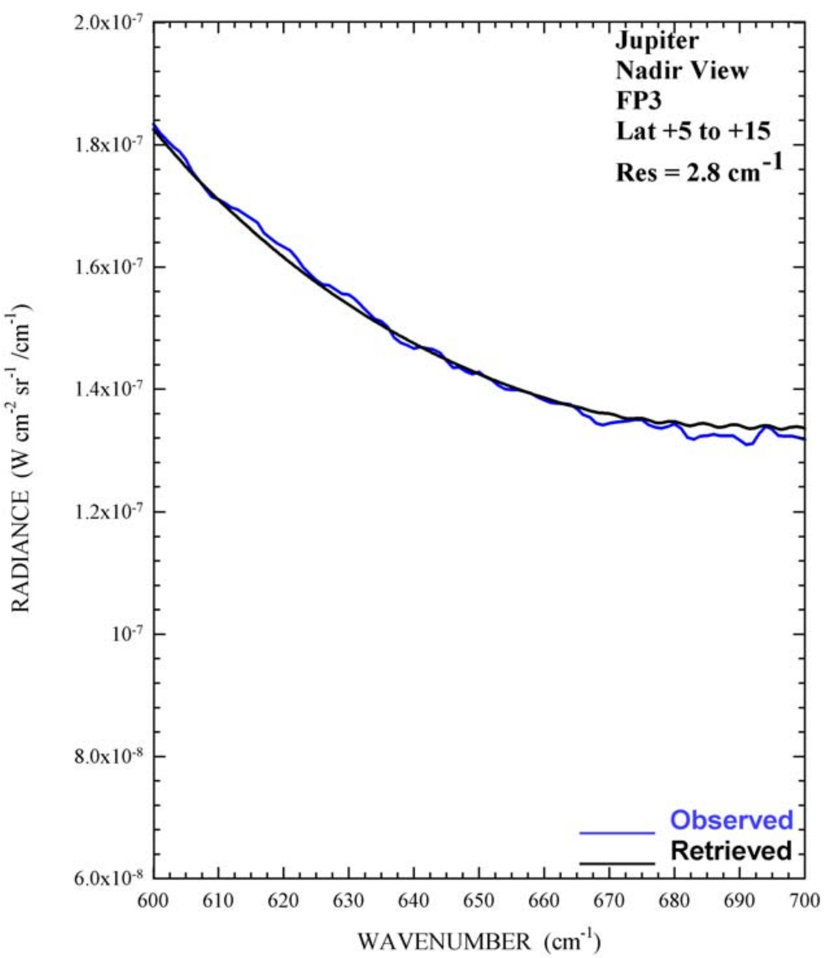


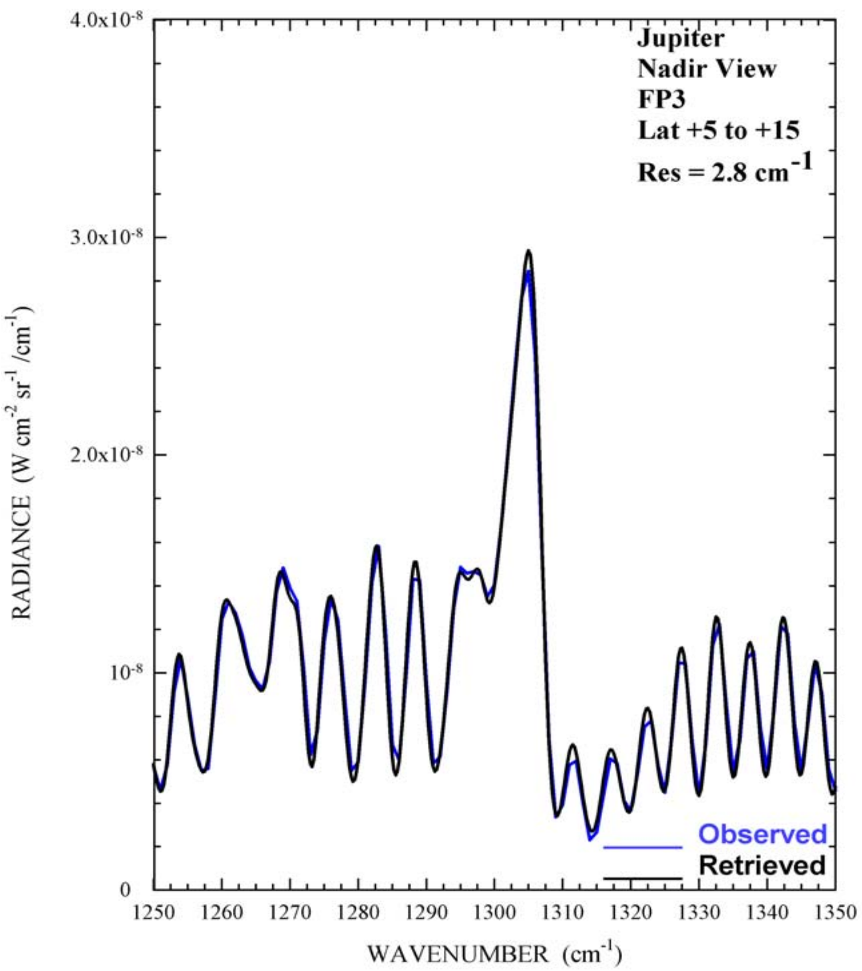
Retrieved latitudinal thermal structure



Retrieved latitudinal distribution of $^{14}NH3$

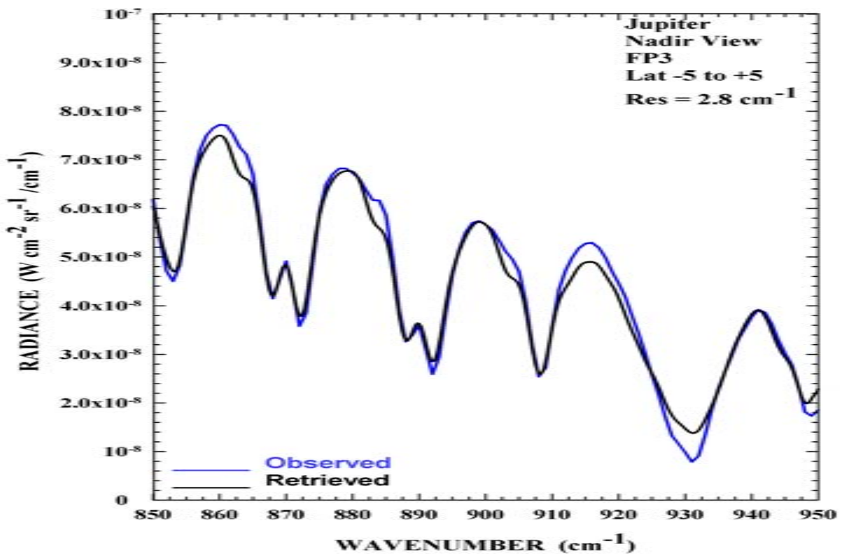
Infrared Spectra of Jupiter

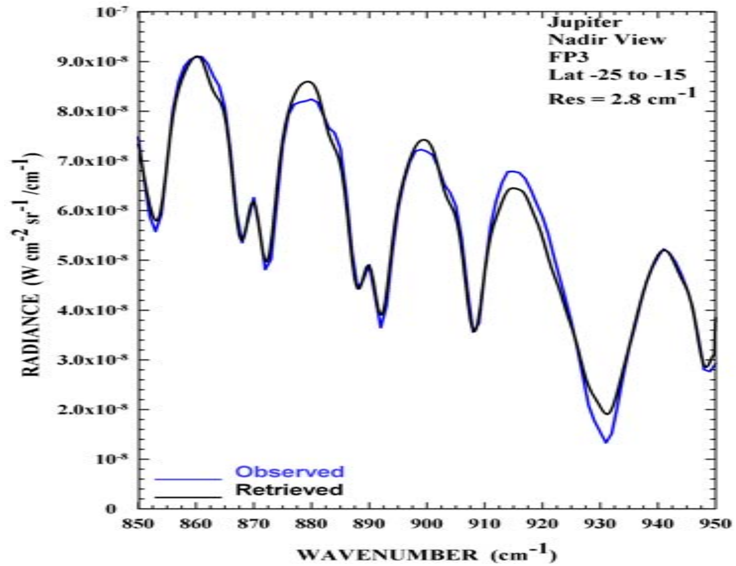


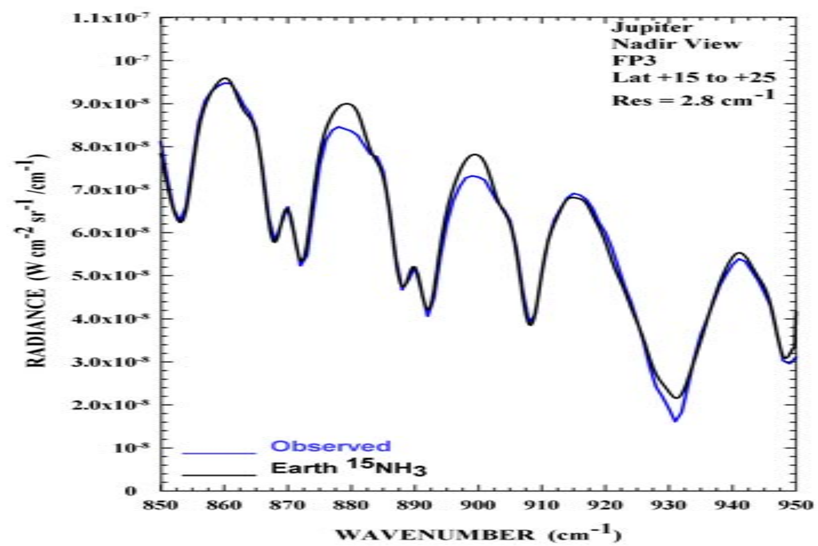


Infrared Spectra of Jupiter

Comparison Plots of the $^{14}NH_3$ Spectra

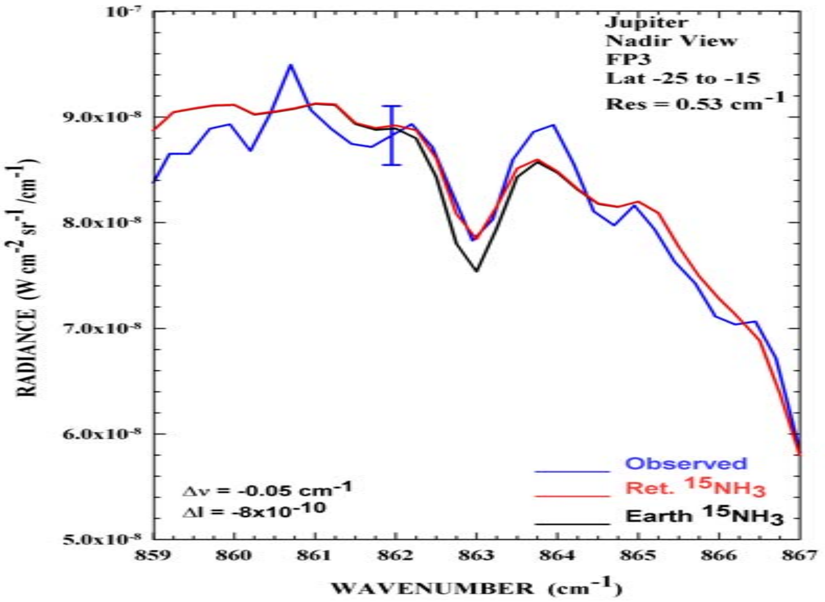


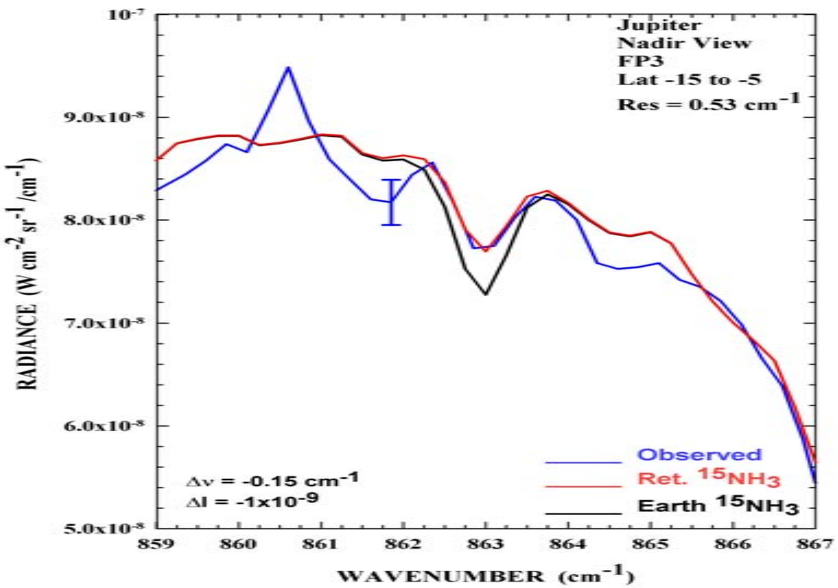


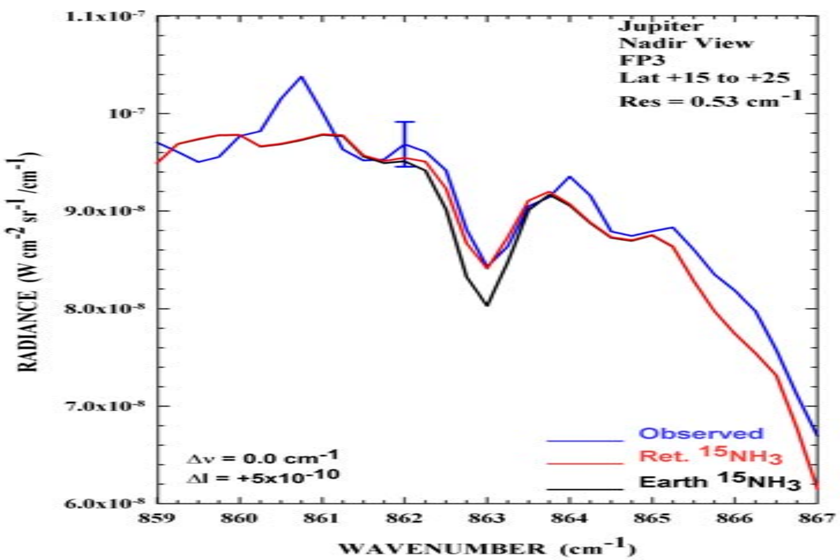


Comparison Plots of the 863 cm^{-1} $^{15}NH_3$ Feature

Comparison Plots of the observed and calculated $^{15}NH_3$ feature at 863 cm^{-1} along with the calculated spectra with the assumed terrestrial ratio ($^{14}NH_3$/ $^{15}NH_3$) of 273.

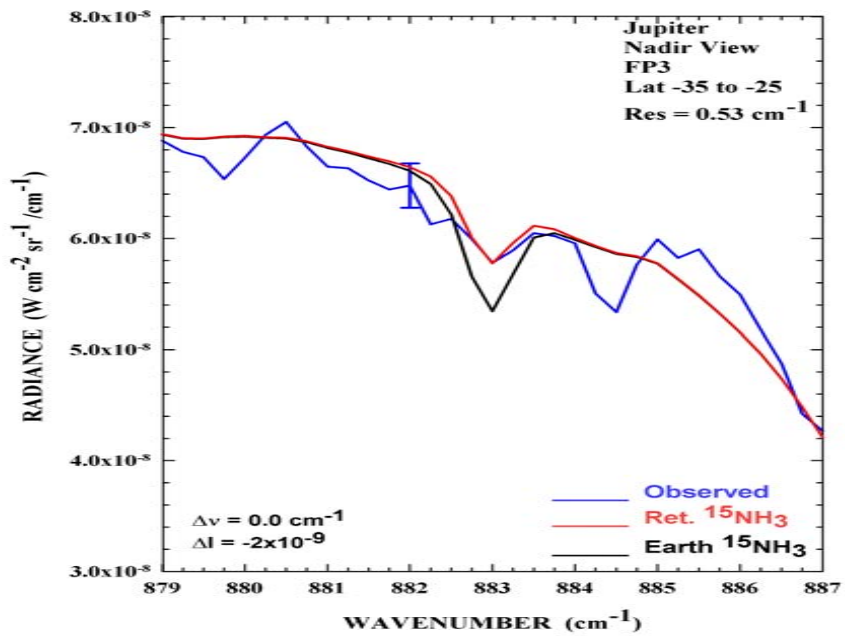


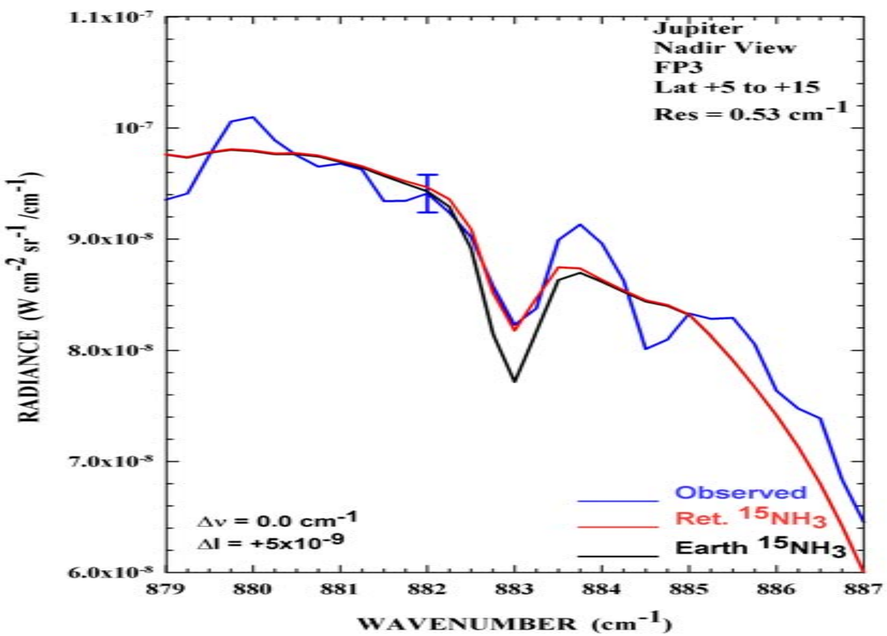


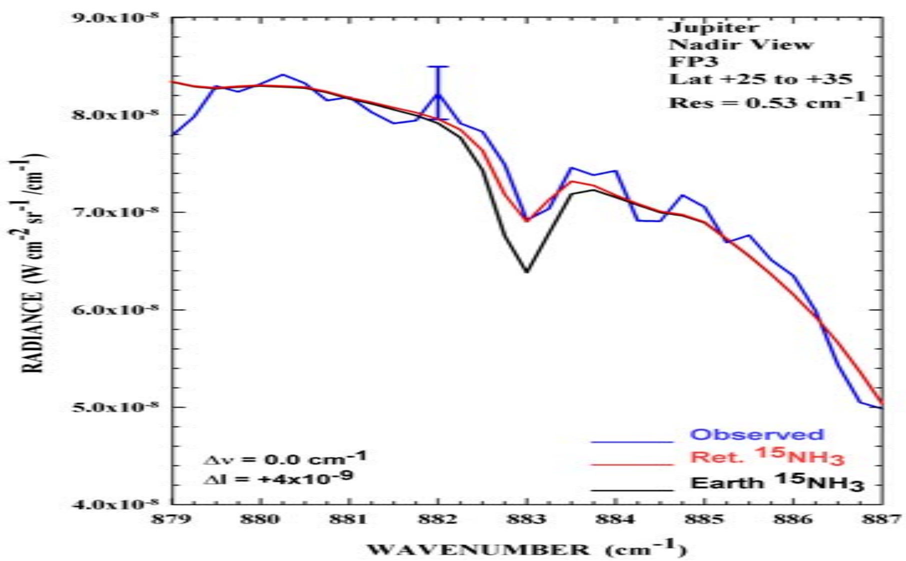


Comparison Plots of the 883 cm^{-1} $^{15}NH_3$ Feature

Comparison Plots of the observed and calculated $^{15}NH_3$ feature at 883 cm^{-1} along with the calculated spectra with the assumed terrestrial ratio ($^{14}NH_3$/ $^{15}NH_3$) of 273.

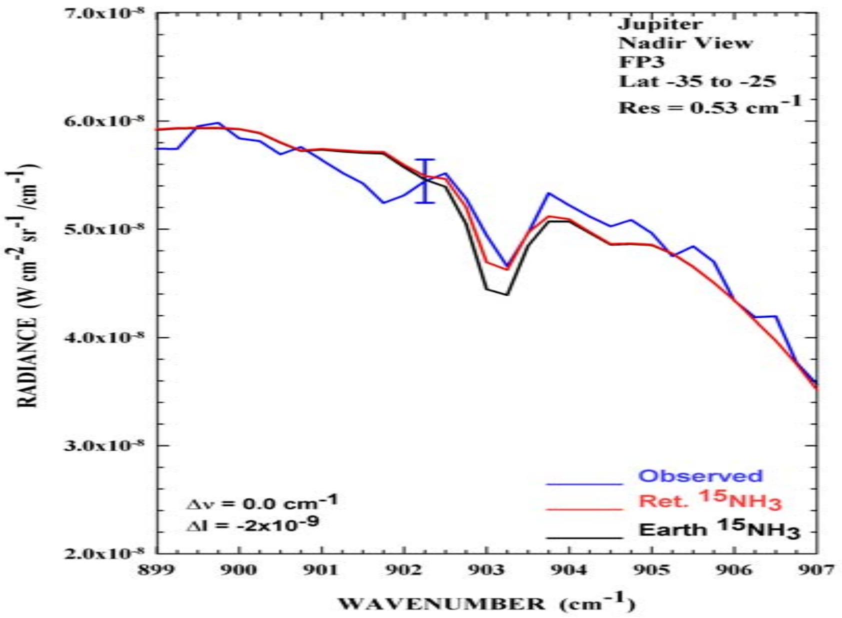


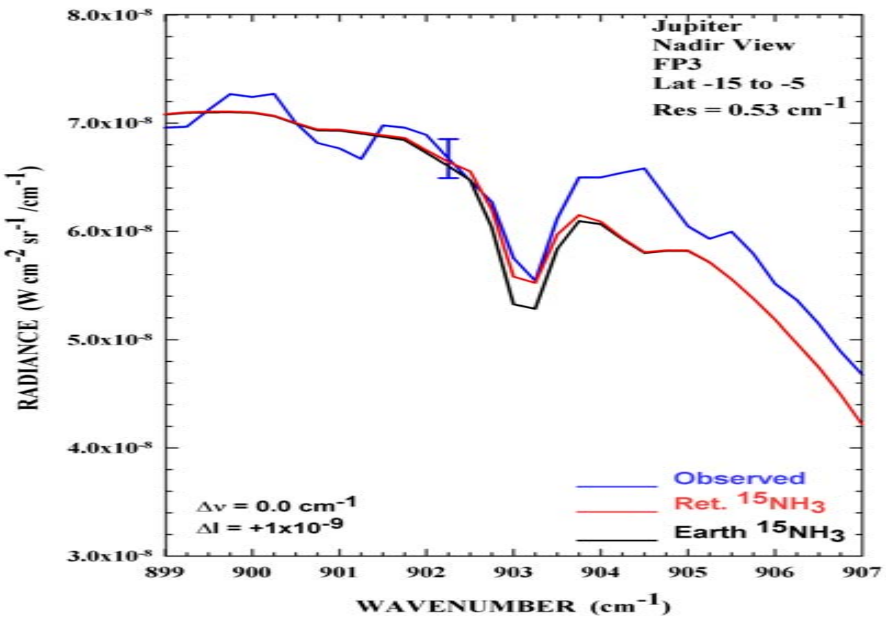


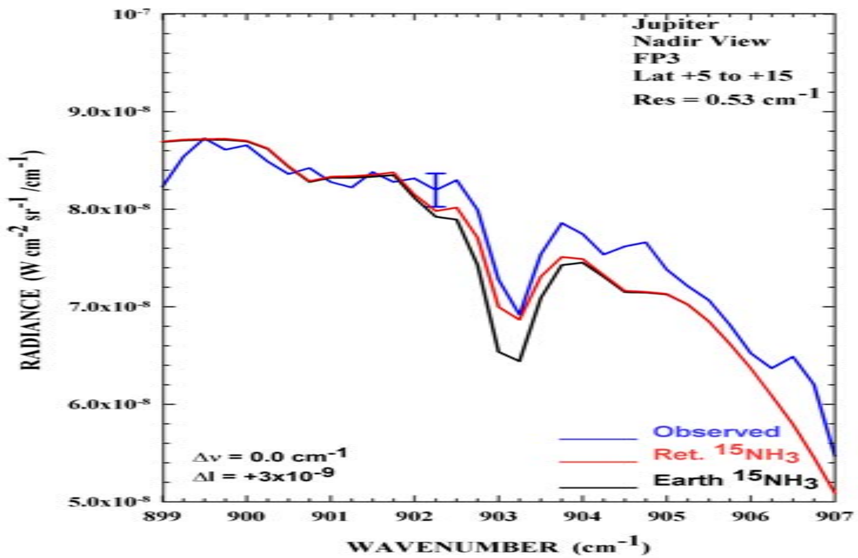


Comparison Plots of the 903 cm^{-1} $^{15}NH_3$ Feature

Comparison Plots of the observed and calculated $^{15}NH_3$ feature at 903 cm^{-1} along with the calculated spectra with the assumed terrestrial ratio ($^{14}NH_3$/ $^{15}NH_3$) of 273.





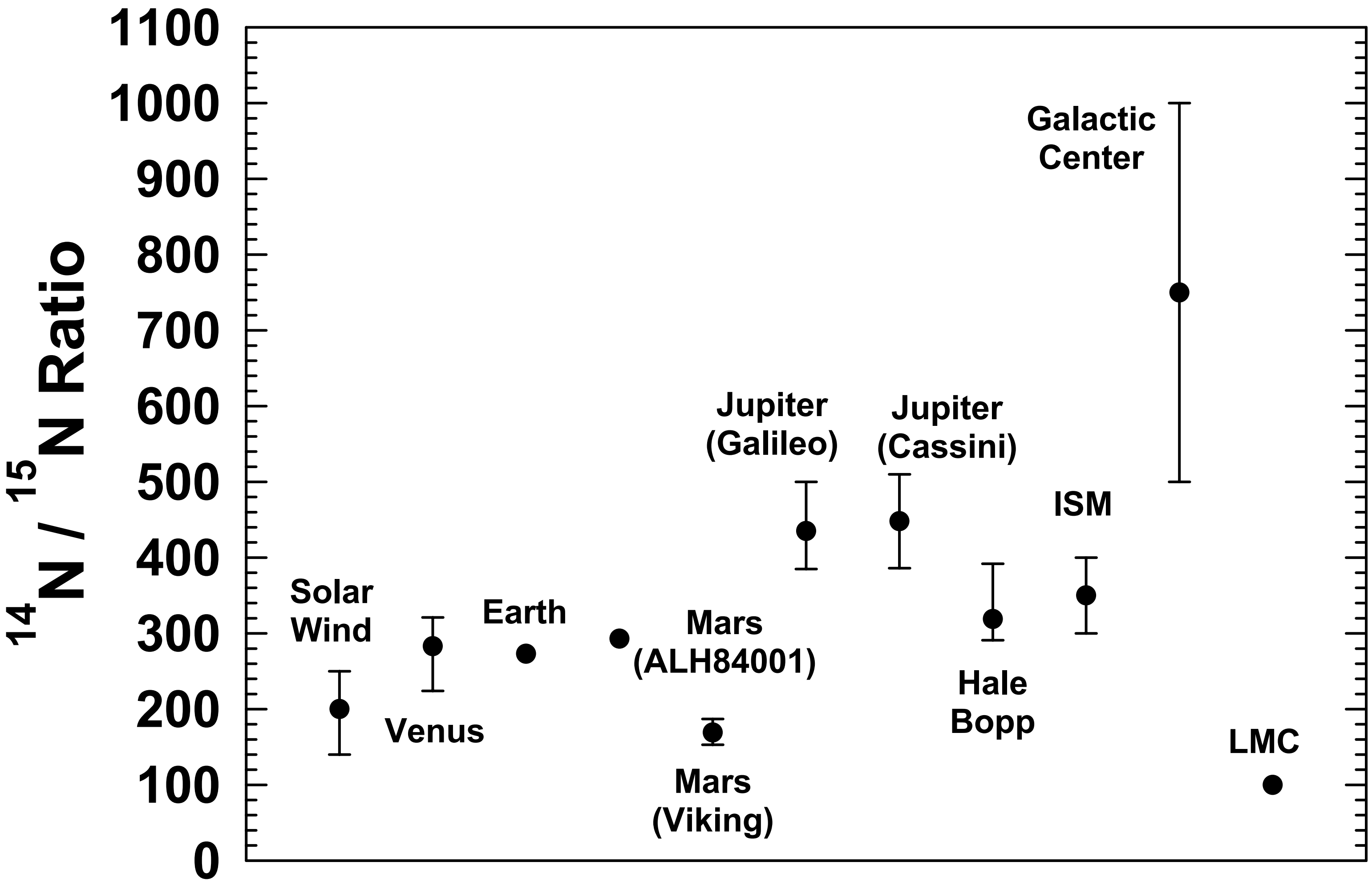


Summary Results of the Retrieved Jupiter's Nitrogen Isotopic Ratio

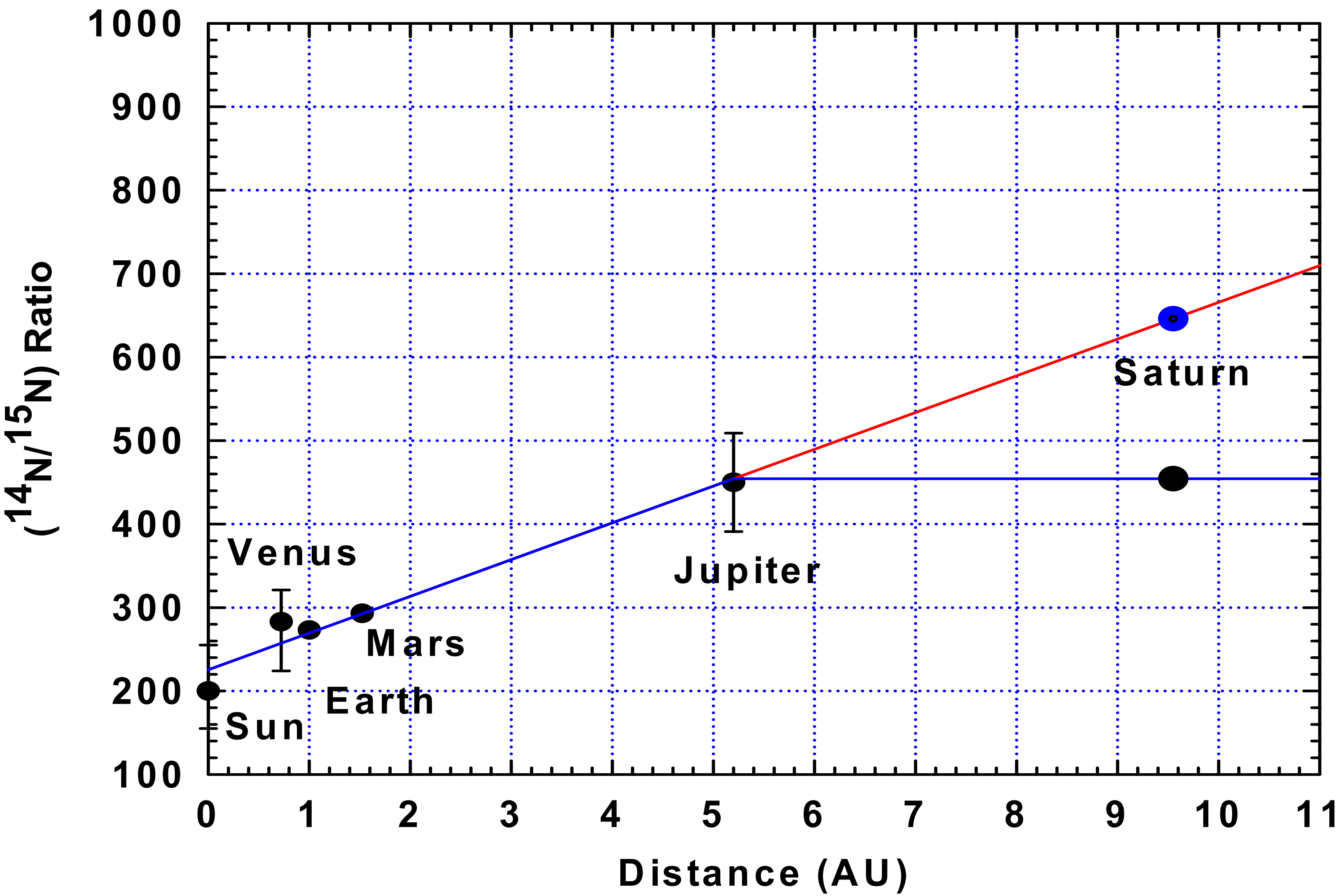
Table 1

	Ret. 15NH3 / 14NH3 Scale Factor				Retrieved 15NH3 / 14NH3		
Latitude Range	863 cm^{-1}	883 cm^{-1}	903 cm^{-1}		863 cm^{-1}	883 cm^{-1}	903 cm^{-1}
+35 to +45	0.66	0.47	0.83		2.42E-03	1.72E-03	3.04E-03
+25 to +35	0.32	0.47	0.91		1.17E-03	1.72E-03	3.33E-03
+15 to +25	0.56	0.33	0.68		2.05E-03	1.21E-03	2.49E-03
+5 to +15	0.79	0.58	0.55		2.89E-03	2.12E-03	2.01E-03
-15 to -5	0.47	0.47	0.64		1.72E-03	1.72E-03	2.34E-03
-25 to -15	0.64	0.51	0.81		2.34E-03	1.87E-03	2.97E-03
-35 to -25	0.77	0.47	0.64		2.82E-03	1.72E-03	2.34E-03
-45 to -35	0.73	0.57	0.83		2.67E-03	2.09E-03	3.04E-03
Mean	0.62	0.48	0.74		2.26E-03	1.77E-03	2.70E-03
Std. Dev	0.16	0.08	0.13		5.90E-04	2.83E-04	4.58E-04
Mean of All	0.61				2.23E-03		
Std. Dev	0.16				5.84E-04		
Std. Dev of Mean	0.033				1.21E-04		
Temp (1 K) Unc.	0.025				9.14E-04		
14 NH3 Unc.	0.073				2.67E-04		
Total Uncertainty	0.08				3.08E-04		
				Ret. 14NH3 / 15NH3			
				Mean of All	448		
				Std. Dev	117		
				Std. Dev of Mean	24		
				Total Uncertainty	62		

Variation of Nitrogen Isotopes in the Galaxy



Jupiter's Nitrogen Isotopic Ratio with distance from the Sun



Nitrogen Isotopic Ratio as a function of distance from the Sun

Discussion/Conclusions

- CIRS results of the nitrogen isotopic ratio are in agreement with the in situ determination by the Galileo Probe. Reassuring, as it validates the Probe mass spectrometer measurements of the nitrogen isotopes, and establishes the validity and accuracy of the measurement from IR spectral features of $^{15}NH_3$.
- From comparison with other astrophysical measurements, the measured value of this important ratio appears to represent the average value of the solar nebula.
- The difference in the Jupiter's and the Earth's nitrogen ratios may stem from the difference in the original carriers of nitrogen. To Jupiter, N_2 was the carrier, and to the Earth it was in the form of nitrogen compounds such as NH_3.
- Production of ^{14}N in low to intermediate mass long-lived stars, with ^{15}N produced in massive stars with short life times leads to a gradual increase in ^{14}N abundances in the galaxy, as massive star formation was more prevalent in early times. This explains the gradient in $^{14}N/^{15}N$ ratio from a high value of 1000 near the galactic center to 300-400 near the position of the Sun.
- In the ISM, ion-molecular reactions can lead to enrichment in $^{15}N/^{14}N$ to a maximum of 30%.
- Gradual increase in ^{14}N in the galaxy implies that $^{14}N/^{15}N$ is higher today than at the time of formation of the solar system.

Discussion/Conclusions

- The $^{14}N/^{15}N$ ratio for the Comet Hale-Bopp is lower than in the interstellar HCN, as the cometary value represents the conditions at the time of formation of the solar system, and was supplied as N_2 not HCN.
- The general agreements are encouraging, but the scenario requires further evaluations.
- The possible role of radiation pressure on dust grains and their distribution in the galaxy as carriers of nitrogen remains to be investigated.
- Cassini/CRS observations of Saturn will provide an opportunity for measurement of this important ratio.

Thank you!